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RESEARCH ON HIGH TEMPERATURE SAND TESTING*

The direct control of the material and mechanical factors that enter into the processing of steel foundry sands and sand mixtures is, in reality, but a means of exercising indirect control over the more fundamental factors of composition, temperature, and time factors which become influential with the introduction of molten metal into a sand mold. Today less thought and study is being given to the room temperature characteristics and properties of sands, and more thought and study is being applied to the physical changes and chemical reactions which are initiated when a rammed sand mass is subjected to the thermal and mechanical forces of metal at pouring temperatures.

Thinking along these lines has led investigators and groups to develop various high-temperature testing procedures to better determine the influence of such changes and reactions in creating or preventing casting surface defects. Essentially, these testing procedures have developed that foundry sand control is basically a matter of controlling (a) surface glazes, (b) sub-surface strengths, (c) internal gas pressures.

One of the initial contributions along these lines was the work of Kleber and Myers at General Steel Castings, using a Dietert dilatometer at temperatures around or above 2000 degrees F, to study the influence of different base sands on surface cracking. They found that the proneness of certain mixtures to surface cracking could be correlated with the unsatisfactory performance of these sands in actual casting operations.

The sand technicians of the Meehanite Metal Corporation have performed additional work along these lines using their own design of apparatus, a piece of testing equipment which essentially combines a dilatometer and a gas measuring unit with a pendulum impact test mechanism, for determining the hot toughness of heated sand specimens. Specimens are heated for a given length of time at a given temperature and then elevated and positioned in a fixture located above the dilatometer. A weighted pendulum is permitted to fall from a fixed height and the impact force required to break the specimen is measured by a suitable gauge. It is reported that information acquired on the importance of controlling hot surface toughness, hot sub-surface strength, and internal gas pressures, has led to a general re-evaluation of their bonding practices and sand control objectives.

It is to be noted that the aforementioned contributions were secured by the use of dilatometers; therefore, the interpretation of the test results is subject to a certain degree of extrapolation. The transfer of heat units through a gaseous medium cannot be expected to promote physical changes and chemical reactions with the same rapidity that prevails when heat transfer is effected by having a sand surface in intimate contact with molten metal. It is almost axiomatic that the better one can duplicate the actual conditions surrounding a given problem, the better one can observe, isolate, define and control whatever changes and reactions which may be fundamental to the problem.

The Steel Founders' Society initiated research project No. 31 at the University of Kentucky to study the fundamentals of foundry sand behavior at steel pouring temperatures. One of the objectives of this project was to investigate the possibilities of developing a sand test that could be used by all steel foundries and which would combine the features of the Meehanite Metal Corporation's impact test and the Caine Dip-Test.

The Dip-Test procedure requires AFS sand specimens to be immersed in molten metal for a given time at a given temperature, and then withdrawn for visual examination. Not only does the test permit studies to be made at times and temperatures more consistent with actual foundry practice, but it also permits the introduction of a number of variations in testing procedure, whereby the variations in metal flow and heat transfer, which occur in the pouring of foundry molds, are simulated.

The usual variations in the Dip-Test involve subjecting test specimens to radiation, continuous immersion, and alternate immersion. To these there can be added 'swishing'; a variation in which the specimen is moved rapidly to and fro in the metal to simulate an erosive flow of metal past a sand face. This variation provides information on the adhesiveness and cohesion of different surface glazes, and their respective abilities to resist being carried away by a metal stream.

Unfortunately, the Dip-Test by itself, is purely qualitative with the exception of the notation of the time of specimen failure. It was hoped that by combining the main features of the Dip-Test and impact test quantitative data could be obtained from specimens exposed to very nearly the same conditions which exist upon pouring molten steel into a mold.

Impact Testing

Meehanite Metal Corporation generously provided their impact testing unit for the investigation. This unit was used to obtain information which enabled the researchers to design a special impacting

* This article, together with the article entitled "Molding Sand Geometry", Journal of Steel Castings Research, Issue No. 3, August, 1955, summarizes the final report on the Steel Founders' Society's Research Project No. 31, "A Study of What Is Fundamental to Foundry Sand Control", conducted at the University of Kentucky.

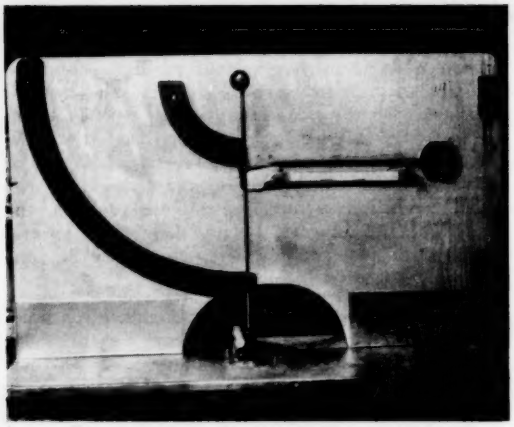

Figure 1—Impact testing unit designed and constructed by the University of Kentucky.

unit to be used with the dipped specimens and to verify and correlate the results obtained from the new unit. The impact testing unit constructed by the University of Kentucky is shown in Figure 1. The important features which distinguish this unit from the Meehanite unit, other than the omission of furnace and dilatometer equipment, are: (1) two specimen rests designed for rapid specimen insertion; (2) an anvil designed to minimize specimen throw and knifing action; (3) adjustable clearances between the anvil and specimen rests.

The specimen rests or holders not only facilitated rapid specimen insertion, but also located the specimen in such a fashion that two planes of fracture were produced, instead of only one. The effect of this feature is to multiply the impact strength and variations in impact strength by two, thereby doubling the sensitivity of the unit. The new design also eliminated the necessity of trimming the specimen to a standard length.

The redesigned anvil and provision for adjustment of the clearances between the anvil and specimen rests resulted from preliminary tests on the Meehanite unit. It was found that the impact energy was definitely affected by the amount of specimen throw (energy absorbed by the sand carried away with the anvil) and the extent to which the specimen failed by shear. The clearances between the specimen holder and the anvil were found to be of prime importance with respect to shearing action. A decrease in clearance resulted in an increase of the shear component within the results.

Preliminary studies showed excellent correlation between the results of the Meehanite impacting unit and the unit constructed by the University of Kentucky. Room temperature impact strengths, obtained from both units, and green compression strength as a function of moisture content of an Ottawa sand, containing 3.5 percent bentonite and

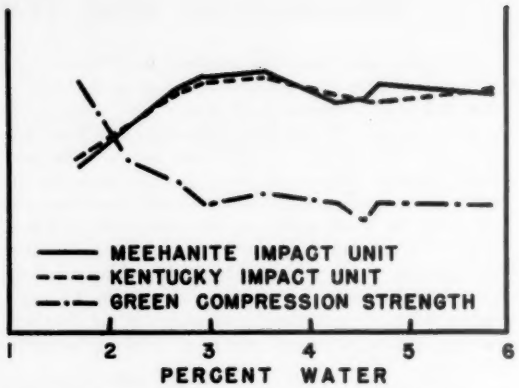

Figure 2—Correlation of room temperature impact results obtained from the Meehanite and Kentucky units. Ottawa sand, 3.5 percent bentonite, 0.5 percent corn flour.

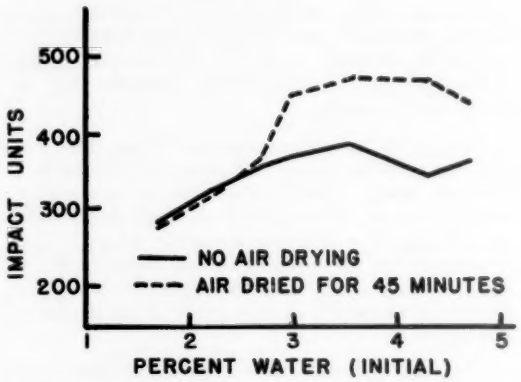

Figure 3—Room temperature impact strength of sand mix tested immediately after specimen preparation and after air drying for 45 minutes. Ottawa sand, 3.5 percent bentonite, 0.5 percent corn flour.

0.5 percent gelatinized corn flour, are shown in Figure 2 to illustrate this correlation. Room temperature and high temperature furnace exposure results obtained from the new equipment not only verified the findings of the Meehanite investigations, but also confirmed the beliefs that impact test data is useful in the study of foundry sands. Figures 3 through 9 verify the usefulness of such tests.

Figure 3 is a plot of the room temperature impact strength of an Ottawa sand mix, containing 3.5 percent bentonite, 0.5 percent gelatinized corn flour and varying amounts of water, immediately after mixing and after air drying for 45 minutes. These curves show that this mix requires a minimum moisture of 3 percent to insure the continuation of tempering during atmospheric evaporation. Figure 4 is the same type of plot as that shown in Figure 3, but for a mix containing 3.5 percent bentonite and 0.5 percent dextrin. These curves show that this dextrin mix requires a minimum moisture content of

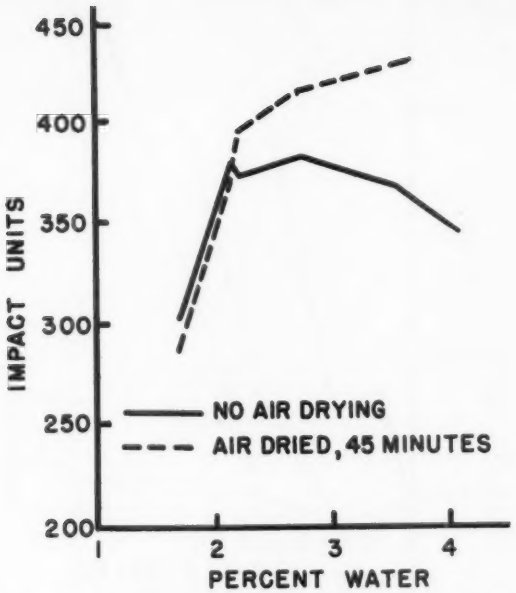

Figure 4—Room temperature impact strength of sand mix tested immediately after specimen preparation and after air drying for 45 minutes. Ottawa sand, 3.5 percent bentonite, 0.5 percent dextrin.

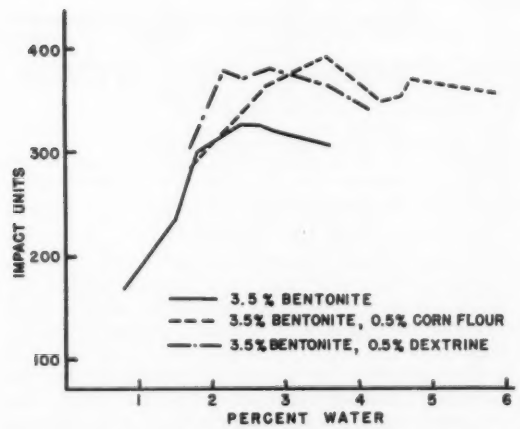

Figure 5—Comparison of room temperature impact strengths of three sand mixes as a function of their moisture content.

2.25 percent to insure the continuation of tempering during atmospheric evaporation. Figure 5 compares the room temperature impact properties of three sand mixes as a function of their moisture content.

Figure 6 illustrates the effect of an increase in furnace temperature and the addition of 1 percent cereal on the high temperature impact properties of a 5.5 percent bentonite sand mix. Figures 7 and 8 illustrate the effect of moisture content on the high

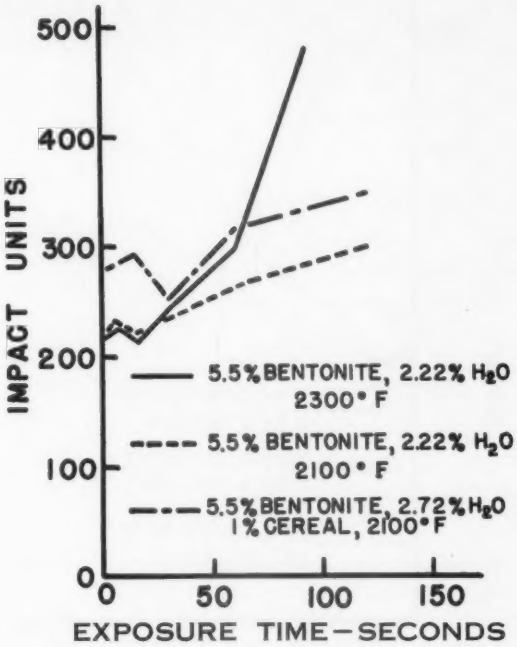

Figure 6—Effect of an increase in testing temperature and a corn flour addition to the high temperature impact properties of a 5.5 percent bentonite mix, furnace exposure.

temperature impact strengths of sand mixes containing 5.5 percent bentonite and 5.5 percent bentonite plus 1 percent cereal, respectively. The effect of varying the bentonite additions, while holding the moisture level constant, is shown in Figure 9.

It can be readily seen from these illustrations that impact testing, particularly high temperature impact testing, is capable of supplying valuable information on the properties of foundry sands.

Dip and Impact Testing

The sand used for the dip and impact testing was a Pennsylvania glass sand bonded with either 5.5 or 8.5 percent bentonite and tempered with water to a good consistency at about 2.5 and 3.2 percent, respectively. The sand was allowed to stand overnight in a sealed jar and was then riddled.

The sand specimens used in this investigation were ¾-inch diameter cylinders produced by pressing a 50 gram sample of sand in a split mold on a standard metallographic press. A pressure of 2500 psi was used, the mold being rapped until the pressure remained constant. The average length of the specimens was 4 inches.

The carbon content of the steels used varied from 0.10 to 0.40 percent, with a high silica content

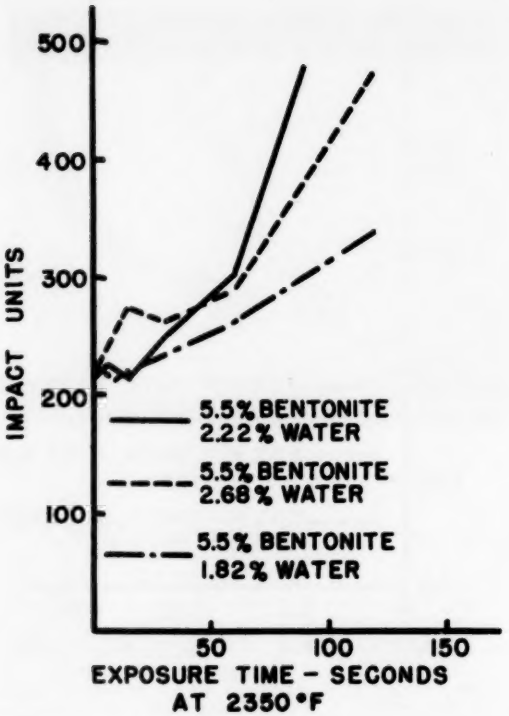

Figure 7—High temperature impact strengths of a sand mix containing 5.5 percent bentonite and varying amounts of water as a function of furnace exposure time. Furnace temperature 2350 degrees F.

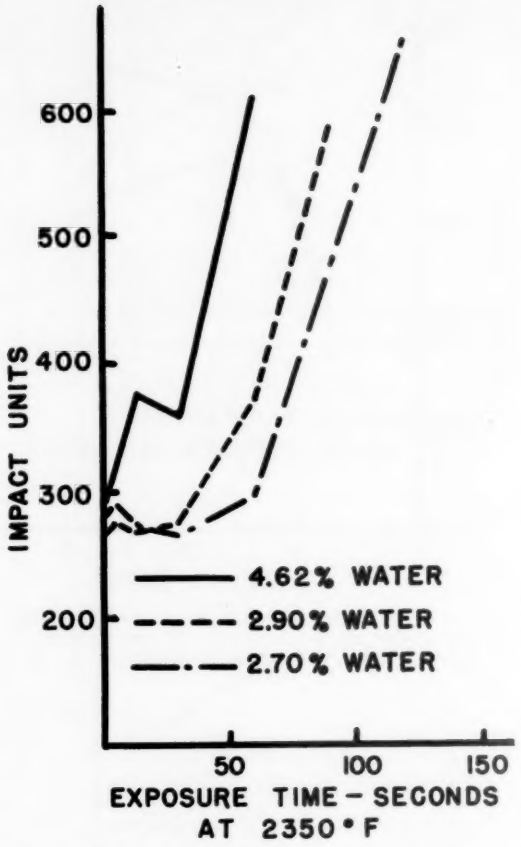

Figure 8—High temperature impact strengths of a sand mix containing 5.5 percent bentonite, 1 percent cereal and varying amounts of water as a function of furnace exposure time. Furnace temperature 2350 degrees F.

accompanying the higher carbon contents. The temperature of the steel was checked with an immersion thermocouple and ranged from 2800 to 3100 degrees F. Thus the bath temperature ranged from 200 to 600 degrees F above the solidification temperature. The steel was melted and held in an induction furnace using a thirty-pound crucible. Input power was increased prior to specimen immersion to compensate for the chilling effect of the specimen.

The attempts to carry out the dip and impact tests were hindered by three problems, one of which proved to be insolvable. These problems were: (1) specimen breakage during immersion; (2) non-uniform heating over the length of the specimen and (3) the adherence of steel remnants to the specimen.

The first and most immediately apparent of the problems was the high rate of specimen breakage. For a time it was thought that the buoyancy effect of the steel was the principal cause of the breakage, since a considerable pressure could be felt on the supporting tongs during immersion. However, experiments in molten lead indicated that buoyancy alone was insufficient to cause breakage, even when the specimen was inserted at an angle. It was concluded, therefore, that the major factor was the fierce buffeting which the specimen received as a result of the violent boiling effect of escaping gases.

This problem was eventually solved by the use of spring-mounted clasps on a pair of tongs. The specimen was not supported by a central arbor as are the regular Caine Dip-Test specimens, but was held around the top edge.

The second problem was that the specimen was subjected to three types of heating along its length. The very bottom of the specimen was subjected to continuous immersion, while a considerable length of the specimen was subjected to alternate immersion. The violent bubbling which resulted from the escape of vapors from the sand so agitated the metal that a considerable length of the specimen was alternately exposed and immersed. The third portion of the specimen (the part above the highest surge of metal) was subjected to radiant heating.

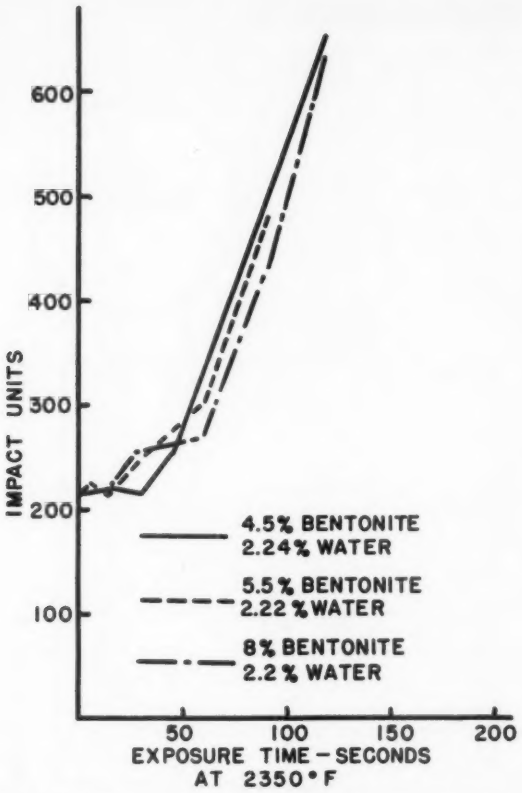

Figure 9—High temperature impact strengths of a sand mix containing varying amounts of bentonite with a constant water content as a function of exposure time. Furnace temperature 2350 degrees F.

The third problem, which proved to be insurmountable, was the adherence of steel to the specimen. All but the lowest portion of the specimen was speckled or streaked with steel remnants. It is believed that the washing or clapping action of the molten steel against the specimen was partly responsible for this adherence. Impact testing of specimens exhibiting adhering steel particles proved to be impossible, as would be expected. The steel remnants reenforced the specimen, even when the remnants were not continuous, so that the impact results were inconsistent and not representative of the sand properties.

An attempt was made to solve the problems of varied heating conditions and adhering steel by using a specimen that could be immersed at least twice as deep as the original specimen. This was accomplished by lengthening the dip specimen and providing a sand extension to protect the specimen tongs from the surging steel.

It was hoped that the increased ferrostatic pressure might contain more of the gases within the specimen,

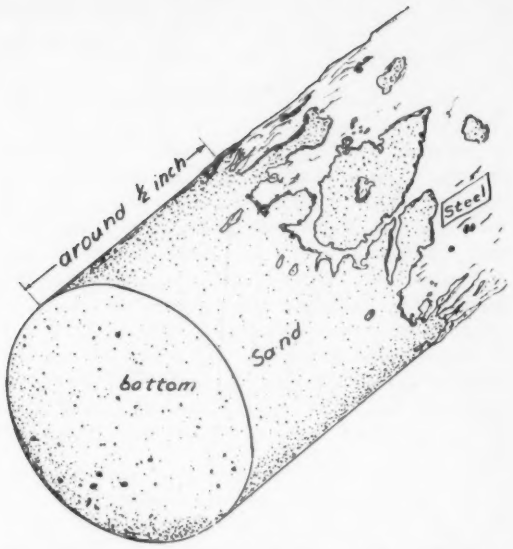

Figure 10—Sketch of solidified steel adhering to dipped specimen.

thus eliminating the violent boiling action. Since the most deeply immersed portion of the original specimen was free of adhering steel, it appeared that the longer specimen might be sufficiently free of steel particles to enable impact testing to be performed.

Unfortunately, the bubbling and steel adherence persisted even with the new specimen. A drawing of one of the specimens exhibiting adhering steel is shown in Figure 10. Results of impact tests under such conditions were, of course, erratic and unreliable, even when the steel remnants were not continuous.

Conclusions:

The results of the attempts to derive a method of testing foundry sands, which combined the impact test with the dip method of exposure, can be summarized as follows:

1. Correlation between the Meehanite impact testing unit and the unit constructed by the University of Kentucky was good.
2. Extended investigations of impact properties at room temperatures and at high temperatures, furnace produced, indicated that impact data is of definite value in the study of foundry sand properties.
3. The adherence of steel to the dipped specimen made it impossible to carry out the dip and impact testing.
4. It appears to be impossible to eliminate the adherence of steel to the dipped specimen.

THE USE OF EXTERNAL CHILLS

*By William D. Emmett**

The Los Angeles Steel Casting Company has from time to time endeavored to use external chills as a means of producing sound steel castings, and the results have varied from quite satisfactory to complete failure. Most of the work performed with the use of external chills in the past was very much hit or miss and based almost entirely on guesswork. However, the company recently completed a systematic investigation of the effect of size and location of external chills on L, T and X sections and bosses, and the effect of pouring temperatures on the effectiveness of the chills. The results of this study have eliminated a great deal of the guesswork involved in the use of external chills.

The sections selected for the research are shown in Figures 1 through 6. The sections were risered as shown and the various methods of chilling are shown with each set of chills numbered according to the sequence of their use.

The risers used, in all cases, were deliberately made oversize to eliminate the possibility of a lack of feed metal. All of the castings were sectioned longitudinally to determine their soundness and those castings exhibiting no visual shrinkage were boiled for twenty minutes in a 1 to 1 HCl solution to determine the extent of shrinkage.

Previous investigations resulted in the conclusion that chills which would satisfactorily aid in the directional solidification of a casting poured at 2800 degrees F would not promote the proper solidification of the same casting poured at 3000 degrees F. This conclusion was found to be erroneous by carefully controlling the pouring temperatures of duplicated tests on all sections. The pouring temperatures were held at 2800, 2900 and 3000 degrees F, measured with an optical pyrometer, and the experiments showed that the pouring temperature had no effect on the solidifying power (heat extraction rate) of a chill of proper size (mass) and location.

Furthermore, the tests indicated that castings produced with chills of incorrect size and/or location exhibited either hot tears or shrinkage regardless of the pouring temperature used.

L Sections

The dimensions and risering of the L section castings are shown in Figure 1. The first casting was made with no chills. Gross shrinkage was found in the junction of the L, i.e., the largest cross-section. A chill was placed at the inside fillet of the L, chill number 1, Figure 1, with a slightly reduced amount of shrinkage at the intersection resulting. However, in this case shrinkage was also observed running lengthwise in the unfed leg.

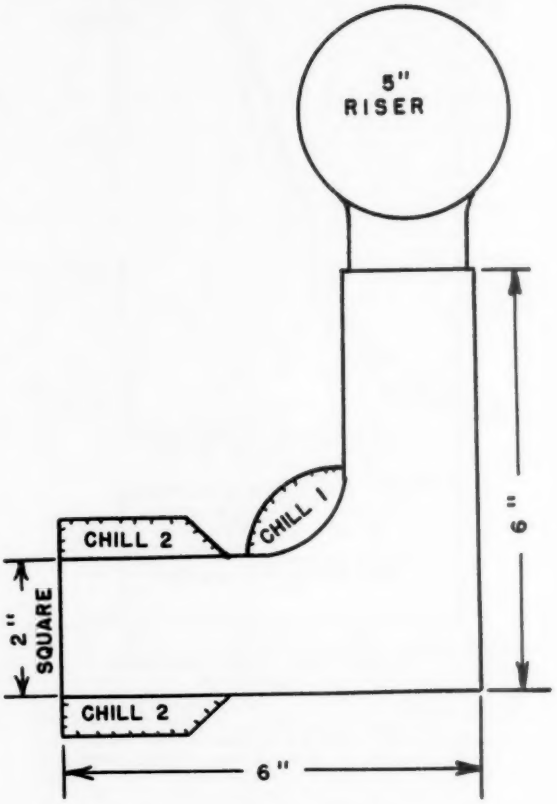

Figure 1—Dimensions and risering of the L section castings. Chill locations are numbered according to their use.

It was quite apparent that both legs were being chilled off too quickly to provide feed metal for the unfed leg and the heavy section. The fillet chill, therefore, was replaced with a chill on each side of the unfed leg, chill set number 2, Figure 1. The resulting casting was sound throughout.

*General Superintendent, Los Angeles Steel Casting Company, Los Angeles, California.

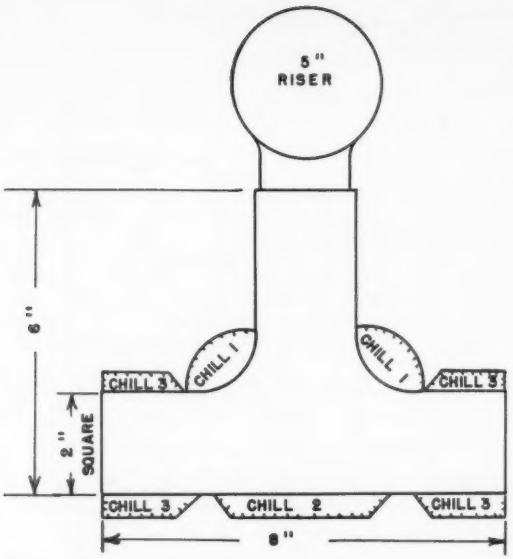

Figure 2—Dimensions and risering of the T section castings. Chill locations are numbered according to their use.

The L section was next fed with a riser at each leg to simulate a casting section being fed from both directions. Again a chill was placed at the inside fillet with gross shrinkage at the junction of the legs again being the result. The same casting was then produced sound by replacing the fillet chill with a bar chill at the outside corner of the junction extending down each leg to the limits of the inside fillet. This arrangement successfully promoted the proper directional solidification from the large hot spot junction to the risers.

T Section

The first T section test casting was made with one riser feeding the leg of the T as shown in Figure 2 and without chills. Gross shrinkage was exhibited at the intersection, as would be expected. Chills were then placed at the two inside fillets, chill set number 1, Figure 2. The results of the use of fillet chills were similar to those for the L section similarly produced, i.e., the gross shrinkage at the intersection was slightly smaller than the casting produced with no chills, but shrinkage also appeared in the arms of the T. This indicated that the arms and feeding leg were being chilled off before the main portion of the arms and the heavy intersection could be properly fed.

Adding a bar chill opposite the feed leg to the two fillet chills previously used, chill sets number 1 and number 2, Figure 2, reduced the size of the shrinkage cavity at the intersection slightly

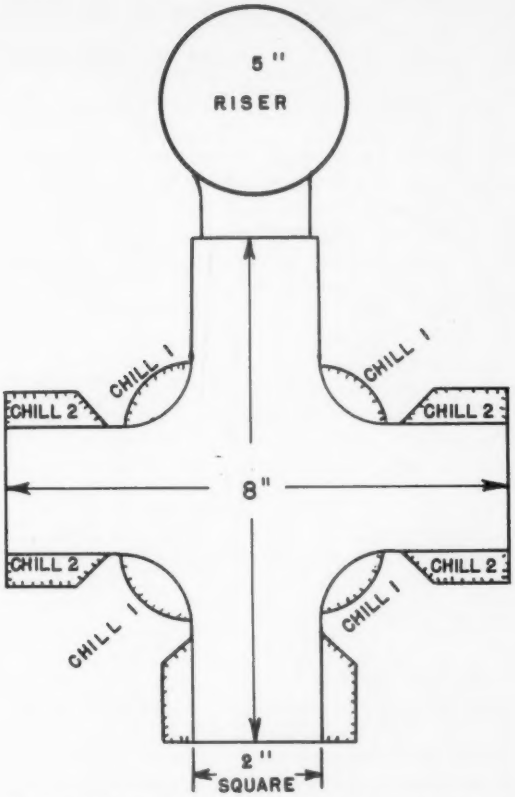

Figure 3—Dimensions and risering of the X section castings. Chill locations are numbered according to their use.

but also increased the extent of shrinkage in the arms. Bar chills placed on each side of each arm but not extending into the fillet area, chill set 3, Figure 2, produced a sound casting.

X Section

The dimensions and risering of the X section castings are shown in Figure 3. The first casting was produced with no chills, with a large shrinkage cavity at the intersection resulting. Fillet chills were then placed at all four fillets, chill set 1, Figure 3, with the results that would be expected from the previous experiments, i.e., the intersection shrinkage was reduced slightly, but shrinkage was observed in the three unfed legs.

The fillet chills were then replaced with bar chills on each side of the unfed legs, chill set number 2, Figure 3. The unfed legs of the resulting castings were sound but a small shrinkage cavity remained in the intersection.

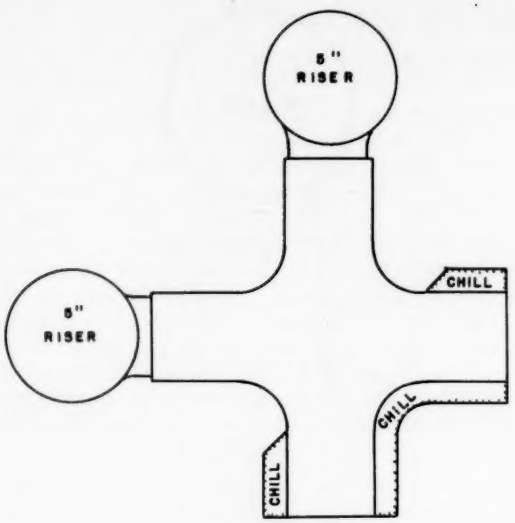

Figure 4—Alternate risering and chilling system used to produce the X section casting.

A second series of X section castings were poured with risers on two adjacent legs as shown in Figure 4. One chill covering each side of two arms and the included fillet opposite the risers was used as is also shown in Figure 4. The resulting castings were found to be free from shrinkage in the arms but contained a small shrinkage cavity in the center of the intersection.

The chill sizes used on all sections were varied to determine the size effect and it became quite apparent that if the chills are increased in thickness over one-half inch hot tearing is encountered. The length and depth of the hot tearing increased as the thickness of the chill was increased over one-half inch.

Boss Chills

The problem of shrinkage in bosses has been a problem of steel casting production for many years. Risering each boss is usually economically unsound and internal chilling has not completely solved the problem. A study of the effect of external chilling on the shrinkage characteristics of bosses was included in this investigation in the hope that some light might be shed on the problem. The design and dimensions of the test casting used are shown in Figure 5. Oversize risers were again used to insure sufficient feed metal and the variation of pouring

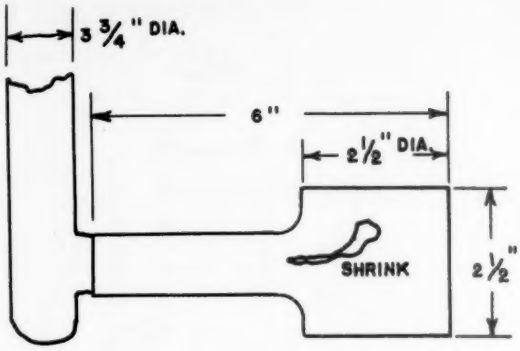

Figure 5—Design, dimensions and risering of boss test casting.

temperature and method of analyzing shrinkage were the same as those used in the previous sections.

The first series of castings were poured with no chills applied. The resulting shrinkage cavity took the form shown in Figure 5. Plate chills, varying from ½ to 2½ inches thick in ¼-inch steps, were placed on the drag face of the boss for the second series of castings. The results showed that the shrinkage cavity had moved closer to the cope face and the tail extending into the arm had disappeared. The thickness of the chill had no apparent effect on the cavity size, however, hot tearing occurred with chills over ½ inch in thickness.

A third series of castings were poured with varying thicknesses of chills on both the cope and drag face of the boss. These castings were all solid with the exception of the casting chilled with ¼ inch thick chills. Once again, hot tearing occurred with chills over ½ inch thick.

The pattern was next changed to give a boss height of 3 inches instead of 2½ inches and chills on both cope and drag faces were applied. A small shrinkage cavity, visible only after etching, was present in all cases. Copper chills were substituted for the steel chills to determine the effect of the greater thermal conductivity, but the results were the same.

It becomes apparent, with this limited amount of research, that the metal will transfer its heat at a given rate even though a chill with higher thermal conductivity than steel is employed. It also appears that the ratio of the boss section to be chilled to the feeding section can be no greater than 2½ to 1 if a completely solid casting is to be produced.

EVALUATION OF FORSTERITE FOR SHELL MOLDING

Harbison-Walker Refractories Company

H. F. Taylor† and R. G. Powell‡, MIT

Introduction

Previous work, done at Massachusetts Institute of Technology for the Steel Founders' Society of America, indicated the possibility of using granulated forsterite as a substitute for silica sand in shell molds for casting plain-carbon and low-alloy steels successfully.(1) The present report covers a further evaluation of forsterite for this application.

Objects of the research were to:

1—investigate the suitability of the grain size and distribution of forsterite obtained at Harbison-Walker Refractories Company with present classifying methods;

2—determine the effect of forsterite flour addition to the forsterite, and

3—establish a practical range of steel temperatures for pouring in forsterite shell molds.

Summary of Results

1—Grain size classification of the forsterite is such as to permit metal penetration when steel is poured at temperatures in excess of 3000 degrees F.

2—Addition of forsterite flour to the forsterite mix does not prevent metal penetration when the steel is poured at temperatures in excess of 3000 degrees F.

3—A practical pouring temperature of 2900-3000 degrees F is suggested for the present resin-bonded forsterite grain size distribution.

Grain Fineness

Forsterite previously used in shell molding studies had a fineness distribution similar to that shown in Table 1. Recently, the Harbison-Walker Refractories Company has constructed a new grinding and classifying plant and the fineness distribution resulting from this classification is also shown in Table 1.

Low strength of shell molds made with granulated magnesia has been related to poor adhesion of phenol-formaldehyde to magnesium oxide.‡ This might indicate that low mold strength may be obtained with forsterite because of its content of MgO. This is probably not the case, however, because it was observed that very fine particles, not necessarily showing in the pan material, are adhering to the surface of the forsterite grains. This has been clearly established by observation under microscope before and after washing the forsterite. These fine particles inhibit a good adhesion of resin to the forsterite grains and are responsible for lowering mold strength. Such difficulty is experienced with most natural sands containing clay, which is the reason washed sands are generally used for shell molding.

Preliminary experiments on surface treatment of the forsterite with resin and solvent indicate that much could be gained by this or a similar practice. If this were done, the fine particles would be detached from the surface of the grains and embodied in the resin binder where they do much less harm. It is possible that treatment could also improve the specific adhesion of the resin.

Good casting surface can be obtained with pouring temperatures up to 3000 degrees F, even though a lack of refractoriness of the resin-forsterite mix (probably resulting from the presence of the resin bond) causes increasing adherence or burn-on as the pouring temperature is raised above 2900 degrees F. The grain fineness is not as important with forsterite

TABLE 1—Grain Size of Forsterite

Sieve U.S. No.	Percent Retained Present	Former†
40	0	—
50	9.8	—
70	31.4	—
100	28.6	24.8
140	17.8	37.4
200	7.2	34.2
270	1.2	3.2
Pan	4.0	0.4
AFS fineness number:	82	110

† Values reported in SFSA Research Report No. 34 published August, 1955.

‡ A.F.S. Preprint No. 57-56.

† Professor, and ‡ Research Assistant, Massachusetts Institute of Technology.
Authorization to publish this report has been given Steel Founders' Society by the Harbison-Walker Refractories Company for whom the research studies were made.

as with silica sand because of the pronounced chilling effect of forsterite, and smooth surface steel castings are produced when poured at normal temperatures. Very satisfactory surfaces, indeed, can be obtained with forsterite of the above fineness and distribution.

The poor wetting properties of forsterite by steel reduce the sharpness of details with decreasing pouring temperature, and it would not seem practical to pour castings in forsterite shell molds at temperatures below 2900 degrees F. At temperatures above 3000 degrees F, with the forsterite under study, considerable metal penetration adds to severe burn-on. Thus, the practical temperature range for pouring steel in shell molds made with present forsterite is limited to 2900-3000 degrees F.

Addition of forsterite flour to the forsterite was not found necessary to obtain smooth casting surfaces with steel poured in this temperature range. Actually, the practice is objectionable because additional resin binder is needed for mold strength and the fines increase burn-on. Additions of 5 and 10 percent forsterite flour to the forsterite failed to minimize metal penetration at temperatures above 3000 degrees F.

An attempt was made to improve wetting of the mold by using 4 percent Fe_2O_3 powder in the shells so as to obtain better sharpness of details at normal pouring temperatures. However, this variation did not prove successful. Dilution of forsterite with more than 50 percent silica sand improves wetting enough to produce sharper details, but also reduces chilling to a point where the same difficulties are obtained as those encountered in plain silica sand shell molds.

Addition of 1 percent magnesium oxide powder to the forsterite did not markedly increase mold refractoriness. Undoubtedly much more MgO should be used. Success in the direction of minimizing burn-on probably would not prevent metal penetration at temperatures above 3000 degrees F. A finer distribution of the forsterite grains without the flour would seem to be the possible answer to this problem. However, pouring temperatures above 3000 degrees F are the exception to general commercial practices.

Measurements of gas evolution were made on shell samples containing forsterite and silica sand. Special mixtures were prepared using 18 grams of refractory and 6 grams of resin. The shell specimens, invested and cured under the same conditions, were crushed and stirred to insure homogeneity. Several measurements were made on 2-gram samples of the materials in an atmosphere of nitrogen at 1600 degrees F. The reason that a mixture of 25 percent resin was used instead of 5 percent was to obtain more gas and minimize errors in reading gas quantities.

TABLE 2—Gas Evolution in a 2-gram Sample of Forsterite and Silica Sand Bonded with 25 Percent Resin

Volume Gas (cc's)	Time (Seconds)	
	Silica Sand	Granulated Forsterite
10	15	8
20	25	17
40	40	33
60	53	44
80	63	54
100	74	64
120	88	73
140	108	86
160	145	104
180	192	136

Results tabulated in Table 2 show that advanced gas evolution is taking place with forsterite. This, however, is not believed to be the reason for improved surfaces obtained on steel castings in forsterite shell molds. The surface chilling ability of forsterite appears to be the fundamental reason.

Conclusion

Gas blow defects and swelling of castings are inhibited when using shell molds made of forsterite for casting plain-carbon and low-alloy steels. Both accomplishments appear related to the chilling ability of forsterite which permits the rapid development of a sufficient casting skin to resist outside gas pressure as well as inside ferrostatic pressure.

It is suggested that more work be done, first, on the possibility of improving the non-wetting of forsterite shell molds by molten steel by using additives, such as non-oxides, in the mix or applying a spray on the shells; for example, aluminum paint. This, indeed, would seem a most practical development since normal pouring temperatures (2850-2950) could be employed and difficulties occurring at high temperature (about 3000 degrees F) would be eliminated.

More testing should be done on surface treatment of forsterite for improved resin adhesion in order to develop a definite procedure for optimum results. A working sample of washed forsterite certainly should be prepared and tested to evaluate the relative importance of MgO and fines upon adhesion. Further work, aimed at decreasing adherence or burn-on, should be done, and tests could be made to investigate the effect of forsterite on penetration with steel poured above 3000 degrees F in case sharper details cannot be obtained below this temperature with better wetting of molds.

INTERGRANULAR FRACTURE IN STEEL CASTINGS

Parts I and II of the British Steel Castings Research Association's Report on the causes of intergranular fracture in steel castings and means of eliminating it were presented in the May 1956 issue of the Journal of Steel Castings Research, Number 5, pages 10-14. A résumé of the first two parts is as follows:

Fractures must occur in metal either through the crystal grains (transgranular or fibrous fracture) or around the grain boundaries (intergranular fracture). Nitrogen is present in all commercial steels in amounts varying from 0.003 to 0.012 percent and in some special types of steel as high as 0.30 percent. The solubility of nitrogen in iron varies as the square root of the pressure.

Nitrogen is an interstitial element in iron and has a strong tendency to form nitrides with both iron and alloying elements. The nitrides formed by both zirconium and titanium are most stable and both of these elements will combine with nearly all the nitrogen in steels to which they are added. Aluminum forms only one nitride in steel (AlN).

Chemical analysis can determine the total nitrogen, the acid soluble nitrogen and the ester-halogen nitrogen. The total nitrogen represents the nitrogen present in steel in all forms. The difference between the soluble and the total nitrogen gives the amount of nitrogen combined as one or more of the insoluble nitrides, such as TiN. The ester-halogen nitrogen content includes only aluminum nitride, zirconium nitride, and nitrogen compounds present in silicon deoxidized steel. The ester-halogen nitrogen in most aluminum deoxidized steels will be almost entirely present as aluminum nitride.

Twelve commercial steels were investigated and analyses were made and reported for acid-soluble nitrogen, ester-halogen nitrogen and total nitrogen. Fractographic examination of each steel was made and findings were reported. All steels but one showed intergranular fractures to some degree. Microspecimens of each steel were carefully prepared and examined. In the majority of cases no grain boundary precipitates could be observed.

The effect of heat treatment on the occurrence of intergranular fracture showed that heat treatments up to 1750 degrees F have little or no effect in removing the intergranular weakness. Temperatures in excess of 2000 degrees F are needed if intergranular weaknesses, due to aluminum nitride, are to be removed.

PART III—Experimental Heats

A number of experimental heats were produced in high-frequency induction furnaces to investigate how additions of aluminum, titanium, zirconium and nitrogen affect the occurrence of intergranular fracture.

Six series of heats were produced and typical analyses of these series heats are found in Table III. The experimental heats were deoxidized with ferro silicon alone and with varying amounts of aluminum (from 1 to 20 pounds per ton). Nitrogen was either added by bubbling the gas through the liquid steel or added as high nitrogen scrap.

The nitrogen and aluminum contents of several of the experimental heats are given in Table IV.

TABLE III—Typical Compositions (percent) of Steel Series A to E

Steel	C	MN	Si	Ni	Cr	Mo
A1	0.30	1.00	0.50	1.00	0.50	.....
B1	0.35	1.30	0.50	0.75	0.50	0.20
C1	0.32	1.37	0.50	0.90	0.60	.....
D1	0.58	1.81	0.50	0.94	0.55	.....
E1	0.56	1.98	0.06	0.83	0.53	.....
F1	0.40	0.36	0.17	0.07	0.04	.....

The experimental heats showed that the susceptibility to intergranular fracture can be produced in both low-alloy and plain-carbon steels containing aluminum and nitrogen by slow cooling after solidification, or by holding in the temperature range of 1475 to 2000 degrees F. The results from several heats show that, with any given nitrogen content, increasing the aluminum content increases the amount of intergranular fracture.

TABLE IV—Nitrogen and Acid-Soluble Aluminum Contents of Experimental Casts

Steel	Acid-Soluble	Ester-Halogen	Total	Acid-Soluble Aluminum
A13	0.0047	0.003	0.0157	0.08
A14	0.0107	.....	0.0159	0.27
A15	0.0111	.....	0.0145	0.29
A16	0.0027	0.0056	.....	.....
	0.0025	.....	0.0137	0.06
A17	0.0093	.....	0.0119	.....
A18	0.0018	0.0057	0.0137	0.19
B1	0.0031	0.0017	0.0148	0.01
B2	0.0065	0.0051	0.0165	0.06
B3	0.0173	0.0140	0.0173	0.18
B4	0.0143	0.0116	0.0153	0.27
B5	0.0159	0.0154	0.0165	0.40
B6	0.0162	0.0165	0.0220	1.00

The analytical results indicate that both aluminum and nitrogen must be present to have intergranular fracture. These results indicated that the embrittlement in the experimental heats was associated with the formation of aluminum nitride, AlN. Also, it was shown that there was a definite correlation between the occurrence of intergranular fracture and the ester-halogen nitrogen content of the steel.

The metallographic studies for series B heats showed that with increasing amounts of aluminum a precipitate developed which was identical in shape and distribution to that identified by Lorig and Elsea [1] as aluminum nitride.

The amount of aluminum nitride which can give rise to intergranular fracture is very low, but the exact minimum content at which intergranular fracture will develop cannot be accurately fixed. However, a reasonable figure of 0.004 percent was suggested for plain carbon steels.

The plain carbon steels are less susceptible to intergranular fracture than the low-alloy steels. This difference is possibly due to the relative resistance to fracture of the matrices of the alloy and the carbon steels. The matrix in the alloy steels is much more resistant to fracture than the matrix of the plain carbon steels; therefore, a given degree of intergranular weakness has a much greater influence on the alloy steel. In plain carbon steels it is difficult to quench and temper a structure throughout; therefore, in the middle section, where the structure contains ferrite and pearlite, the cleavage strength is lower than the intergranular cohesion and brittle fracture occurs rather than intergranular fracture; structures other than tempered martensite in low-alloy steels generally result in brittle cleavage, although in the quenched and tempered state the fracture is almost entirely intergranular.

The results for series B and F heats showed that a very small percentage of nitrogen as aluminum nitride and distributed at the austenite grain boundaries is sufficient to cause intergranular fracture. A nitrogen content of 0.005 percent combined with 0.01 percent aluminum is all that appeared to be necessary.

Also, the results showed that it is possible to have too much aluminum nitride present to give intergranular fracture. For example, a heat to which 20 pounds of aluminum per ton of steel were added had an aluminum content of 1.0 percent and an ester-halogen nitrogen content of 0.0165 percent and there was no intergranular fracture present in the quenched and tempered specimens; however, with 10 pounds of aluminum per ton of steel the fracture was completely intergranular.

The work of Lorig and Elsea [1] had also shown that the effect of high aluminum additions to steel was to decrease the amount of intergranular fracture. They found that the occurrence of intergranular fracture was at a maximum in steel when 8 pounds of aluminum per ton of steel had been added, and that it decreased with additions of 20 and 28 pounds of aluminum per ton of steel.

The data showed that titanium and zirconium as ferro alloys may successfully be used for deoxidation without causing intergranular fracture. The titanium addition was equivalent to 19 pounds (20 percent titanium) per ton. The addition of 19 pounds of 20 percent ferro-titanium, together with an aluminum addition (5 pounds per ton), which is sufficient by itself to cause intergranular fracture, successfully prevented the development of the intergranular weakness.

Analytical results showed that titanium, which combines preferentially with nitrogen, reduced the nitrogen available to form aluminum nitride to such a low value that no intergranular fracture occurred.

The mechanical properties of steels deoxidized with titanium, aluminum, and aluminum and titanium are presented in Table V.

A comparison of the intergranular fractures found in the commercial steels with those found in the experimental heats showed:

(1) The fracture facets had the same general appearance.

(2) In each case the intergranular weakness responded to heat treatment in a similar manner.

(3) The acid-soluble and ester-halogen nitrogen contents of the commercial steels were equal to or greater than those in many of the experimental steels.

(4) Most of the experimental steels showed an obvious grain boundary precipitate (aluminum nitride) while most of the commercial steel did not show grain boundary precipitate.

PART IV—Prevention of Intergranular Fracture

Although grain size, composition and internal stresses may influence the susceptibility of a steel to intergranular failure, the two principal variables are (1) the aluminum nitride content, and (2) the rate of cooling through the range 2100 to 1300 degrees F. The first of the variables can be controlled by the aluminum and nitrogen contents of the steel which, in turn, is dependent upon the nitrogen content of the scrap and ferro-alloys, the method of melting, the degree of oxidation of the bath, and the amount of aluminum finally added.

TABLE V—Tensile Test Results on Differently Heat Treated Specimens Prepared from Steels Deoxidized by Ferro-Titanium, Aluminum, and Ferro-Titanium Plus Aluminum Additions.

Treatment	Steel	Additions	Yield Point psi	Max. Stress psi	Elong.	Reduction	Fracture
Furnace-cooled from 900°C.	A16	Ferro-titanium only	54,000	90,800	53.5	25	Ductile
	A17	Aluminum only	56,000	88,000	36	15.2	Intergranular and ductile
	A18	Ferro-titanium and aluminum	52,800	88,600	43.5	22.6	Ductile
Oil-quenched 900°F. Tempered 650°C. 3 hours.	A16	Ferro-titanium only	88.200	103,000	31	18.8	Ductile
	A17	Aluminum only	83,200	100,000	16.5	4.9	Intergranular
Water quenched	A18	Ferro-titanium and aluminum	86,300	101,600	32	21.5	Ductile

The second major factor which controls the development of intergranular fracture — the rate of cooling of the casting — depends on the size and shape of the casting.

A most promising line of approach in avoiding intergranular fracture is the use of either titanium or zirconium to remove the nitrogen. The results of the experimental heats A16 to 18 showed that titanium additions which will leave 0.08—0.15 percent residual titanium in the steel will prevent intergranular fracture from developing even in the presence of aluminum but, unfortunately, give rise to Type II sulfide inclusions. When the amount of titanium in the steel is less than 0.02 percent, Type II inclusions are not formed according to Sims, Saller and Boulger [8].

Conclusions

The principal conclusions reached were:

(1) In both low-alloy and in plain-carbon steels, aluminum nitride precipitation at the austenite grain boundaries can give rise to intergranular fracture.

(2) The susceptibility to intergranular fracture of a steel containing aluminum and nitrogen depends on the aluminum nitride content of the steel (which is controlled by the amounts of aluminum and nitrogen present) and the time and temperature between 2100 and 1300 degrees F.

(3) The minimum amounts of nitrogen present as aluminum nitride which can give rise to intergranular fracture appear to be 0.002 percent for low alloy steels and 0.004 percent for plain carbon steels.

(4) All the commercial steels analyzed contained aluminum nitride in amounts greater than the minimum which gave rise to intergranular fracture in the experimental melts.

(5) Intergranular fracture was absent from a steel to which 20 pounds of aluminum per ton of steel had been added; the aluminum nitride precipitated on already existing nuclei and did not form a grain boundary precipitate.

(6) The addition of titanium prevented the occurrence of intergranular fracture by combining preferentially with the nitrogen.

(7) The intergranular fracture in both an experimental and a commercial steel was removed by heating at 2280 degrees F, for 1½ hours. Intergranular fracture was present in specimens subsequently held at temperatures below 2100 degrees F for a commercial steel and below 2000 degrees F for an experimental melt.

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PRESSURIZED RISERS

The concept of improving the efficiency of risers on castings by applying pressure to the liquid metal contained therein, and thereby reducing their size and number and increasing the utilization of molten steel, is not novel.

The use of gas-producing cartridges in blind risers has been described by Jazwinski and Finch[1], and the application of pressure by the use of compressed gas (nitrogen or air) has been described in Russian literature. A British patent covering the application of air pressure to the ingate of a mold after casting was granted to the Metropolitan-Vickers Electrical Company Ltd. in 1952.[2]

An investigation of these techniques, which led to generally unfavorable commercial application of pressurized risers, was reported by Briggs and Taylor.[3]

Academically the principle of pressurizing risers is essentially sound. If pressure can be successfully applied to liquid steel in a riser, each one atmosphere of gas pressure will improve the feeding efficiency of the riser to the same extent as if the height of molten steel was increased by approximately 4 ft. The use of gas-producing cartridges was unfavorably criticized by Briggs and Taylor on the valid ground that the evolution of gas was largely uncontrollable. Their equally unfavorable comments on the use of compressed gases, applied to small castings, and, therefore, the technique, was not shown to its best advantage. It is possible that severe metal penetration and mold deformation, which take place in small castings, would not result in large castings of large superficial area, because of the large ratio of casting size to riser size.

It is now reported from Russian and Continental sources that the pressurized user technique is now being applied successfully in steel as well as in iron and non-ferrous foundries. Just how controllable and commercially successful is the method, is not known.

Descriptions of Russian work in this field have been given by Kononow[4] and Desnizki[5]. The Russian method of application of pressure to the riser is illustrated by Figure 1. A channel for the supply of compressed air is provided by a steel tube, which is molded into the top part. Into the end of this tube is inserted a pencil, formed of ordinary molding sand or more refractory chamotte and containing a number of narrow channels. The ends of these channels are luted up with a thin layer of slurry to prevent molten steel penetrating the channels and freezing during the filling of the mold. The riser is molded in a facing sand of very low gas permeability. The mold and riser are filled with liquid steel, but the application of pressure is delayed until a solid skin has formed around the riser, which then constitutes its own pressure vessel.

Compressed air is turned on, at first at a relatively low pressure. The pressure is increased as solidification proceeds and the solidified skin becomes thicker and, consequently, more able to withstand the applied pressure. Pressures as high as 5 atmospheres (60 lb/sq in.), equivalent to a ferrostatic head of 20 ft, may be applied to large risers. The Russian papers give full details of the sizes of riser to be used for castings of various sections and the time schedule for the application and increase of pressure to risers of various sizes. Riser sizes are generally based on a height diameter: diameter ratio of 1 : 1. Typical examples of the increased yield of steel obtained by the technique, taken from the paper by Kononow, are given in Table I.

The improved yield of steel results from the decreased height of the riser and not a reduction in diameter and, more importantly, from the fact that the feeding range is much greater, so that the number of risers may be reduced. In addition to the increased yield of steel, it is claimed, and it may well be believed, that the castings are appreci-

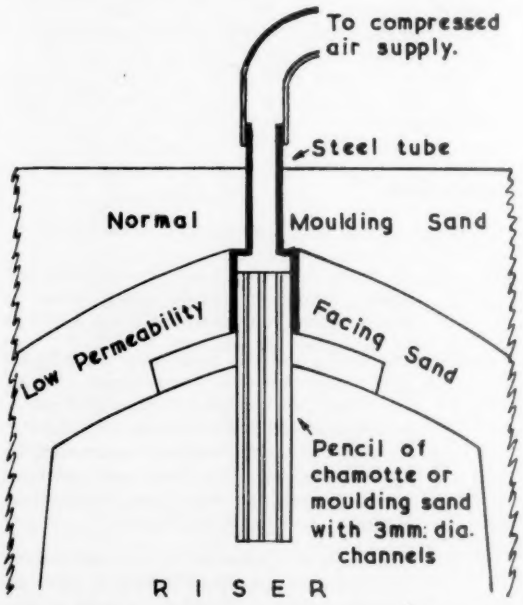

Figure 1. Application of compressed air to riser (Russian method).

ably sounder, the improved feeding efficiency being associated with the substantial elimination of looseness of structure in those portions of the casting last to solidify. It is, however, to be noted that the technique can be effective only in cases where the configuration of the casting is favorable to the progressive solidification of the casting towards the riser, i.e., the technique cannot assist in feeding a thick section through a thin one.

The reader should look at the top columns under the designation of "Yield" in Table I with considerable degree of skepticism. In the first place, the dimensions of the so-called usual risers are not given. SFSA research has shown that a riser height: diameter ratio of 1 : 1 is ideal for normal risers without pressure applications. Furthermore, it is believed that a pressurized riser could not be smaller than a non-pressurized riser because the rates of solidification would be similar and, if anything, the air or gas at the center of the riser would tend to speed up the solidification of the pressure riser.

The only way in which the riser yield could be improved would be through greatly increased feeding distances; fewer risers, therefore, would be required. It is claimed that the feeding range is much greater when pressurized risers are used. This point definitely needs further confirmation. Perhaps the same order of results can be obtained by the use of exothermic pipe eliminator and/or exothermic riser sleeves.

It is very probable that the pressurized riser technique is not 100 percent reliable. If, for example, the pressure is applied too soon, the solidified skin of the riser may be ruptured and, while some protection against the consequences is provided by the layer of low permeability facing sand, a leakage channel may develop. Also, the Russian papers hint that sometimes the refractory pencil, through which the pressure is applied, may fracture, and it is advisable, especially with large risers, to provide two such pencils to guard against the fracture of one of them. Obviously, if leakage or fracture of pencil occurs, the consequences can be very serious, since the riser may be improperly placed to provide a sound casting by normal gravity feeding.

Recently described Continental developments[6] constitute an advance on the Russian technique in two respects:

(1) in improving the sealing of the riser, thereby making the process more reliable, and

(2) in combining the application of pressure with the use of exothermic materials, thereby keeping the metal in the riser liquid for a longer period and producing further economies in the size of risers.

These improvements are illustrated by Figure 2. The riser is sealed by a cover made of grey iron, which contains a channel by means of which the riser may be vented and air pressure supplied both to the surface of the steel and to the interior through a pencil similar in design to that used in the Russian process, except that it is reenforced by metal rods. The grey iron cover carries a peripheral lug. This has the effect of chilling the steel when the riser is filled and automatically providing a sealing ring of solidified steel. The pencil itself is made of moldable exorthermic material and an exothermic

TABLE I.—Comparison of yields obtained in the production of a range of castings using conventional feeding risers and those working under compressed air (Kononow).

Type of Casting	Dimensions of Casting in.	Weight of Casting	Yield with Usual Risers %	Yield with Pressure Risers %
Rudder	44½ × 72¾	3 tons	40	70
Housing	71 × 55 × 27½	1½ tons	50	78
Steam (Chest)	51 dia. × 22¼	17 cwt	44	84
Guide Wheel	47¼ dia. × 6	1¼ tons	40	83
Cog Wheel	84 dia. × 7½	2 tons	40	89.7
Bracket	86½ × 31½ × 8	15 cwt	34	72
Sleeve	20 dia. × 19½	5 cwt	50	88
Segment for Underground Railway (18 sizes)	67 × 59 × 32	5½ tons	60	83
Gear Wheel	23 dia. × 5	2 cwt	40	70
Ring	8½ × 62 × 8½	2¼ tons	60	75
Bed	71 × 16 × 8	1½ tons	50	80
Die Block	71 × 12 × 6	16 cwt	50	60
Die Block	71 × 16 × 6	1¼ tons	50	80
Chain Links (14 sizes)	From 40½ dia. × 5½ to 70 dia. × 8¾	2-8 cwt	45-50	75-80
Die Blocks (29 sizes)	From 59 dia. × 6¼ to 98½ dia. × 28	2 cwt-1¼ tons	45-50	65-75

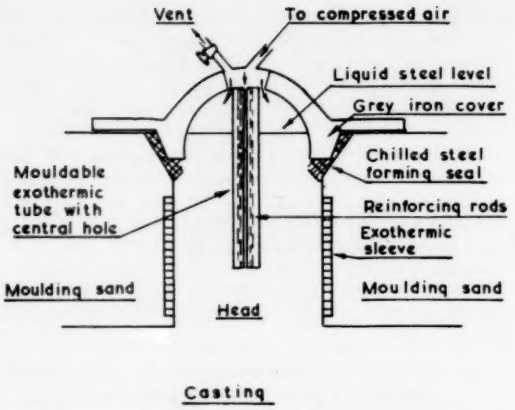

Figure 2. Arrangement for supply of compressed air to riser as practised at Cie Carels, Ghent.

sleeve is molded around the riser, thereby providing a source of heat to keep the riser molten for a considerable period of time, during which the molten steel is forced by the air pressure into the solidifying casting.

A pressure of two atmospheres can be applied to the riser within 30 seconds of filling the mold and is maintained for the whole period of solidification of the casting. It is claimed that this method is being successfully applied to the production of iron and steel castings up to 10 tons in weight. The yield in favorable cases is as high as 85 percent and the production costs are considerably reduced as a consequence of the reduced number and diameter of the risers. The Russians claim that, with castings of about 9-inch section, the feeding range can be as much as 10 to 11 feet.

It is obvious that this technique, which requires very little in the way of special equipment, offers important advantages and is worth serious consideration. The Continental process is said to be protected by a British patent application. This patent is, however, not yet open to inspection, so that an estimation cannot be made of its strength. Since the principle of pressure application to risers has been known for some time, it may be presumed that a valid patent can only be obtained on the method by which the pressure is applied to the riser. Until the patent is published and an assessment made, therefore, it should not be assumed that there are not other equally effective methods of applying this technique, which do not contravene this patent.

It is not known whether or not an application has been made for a United States patent on these developments. However, studies should be made to look into the exaggerated Russian claims as to feeding distances in heavy sections.

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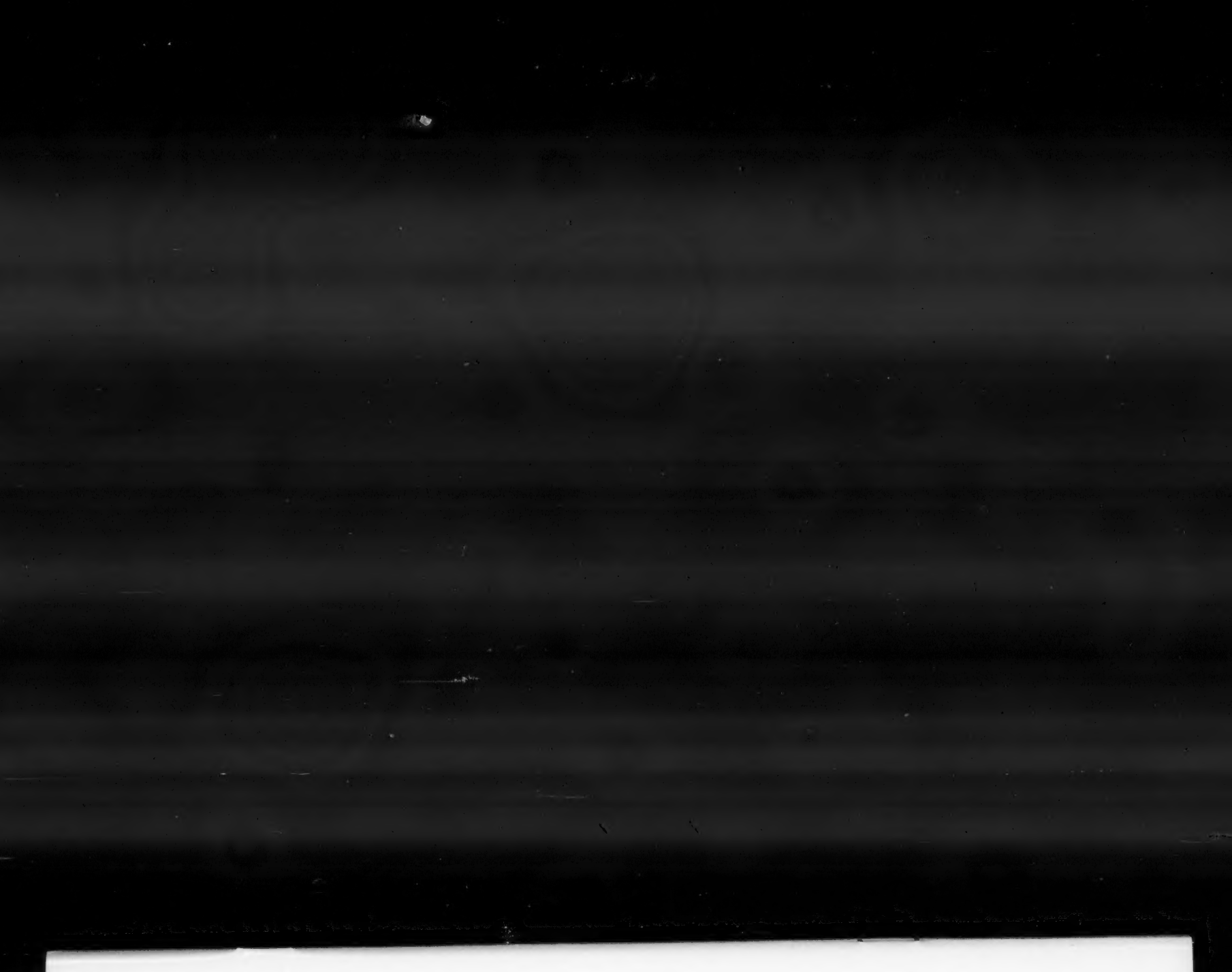
INTENSIFICATION OF FEEDER HEAD HEATING*

The May issue of *STAL*, the Russian monthly journal, reported that efforts had been made at the Hammer and Sickle works, Moscow, to reduce the amount of discard in the rolling of killed steels by intensifying the heating of the feeder head portion by burning powder consisting of 75 percent ferrosilicon in an oxygen jet. This method has been applied to ingots weighing 800 kg (1760 pounds) and to shaped castings of up to 18 tons, and can be recommended for heavy ingots and castings. For lighter ingots, the oxygen for igniting the ferrosilicon powder was produced by the decomposition of sodium nitrate at a high temperature. The optimum mixture for small bottom pour ingots consisted of 70 percent ferrosilicon, 20 percent sodium nitrate, and 10 percent firebrick powder. The metal temperature rose 30 to 40 degrees F after ignition of the mixture.

Certain excess of silicon is essential to prevent, at least partially, decarbonization of the metal in the feeder head region. The excess silicon partly diffuses in the layer of metal at the boundaries of the pipe to a depth of about ½ to 1 inch, but this is removed by discard.

* Abstract from *The British Steelmaker*, August 1957.